Report of the Defense Science Board Task Force on the NATIONAL AEROSPACE PLANE (NASP)

September 1988

Office of the Under Secretary of Defense for Acquisition
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Diane L.H. Evans

22b. TELEPHONE *(Include Area Code)*
(202) 695-4158/6463

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DEFENSE SCIENCE BOARD

September 21, 1988

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE (ACQUISITION)

SUBJECT: Report of the Defense Science Board Task Force on the National Aerospace Plane (NASP)

I am pleased to forward the final report of the Defense Science Board Task Force on the National Aerospace Plane (NASP). The Task Force, chaired by Dr. Joseph F. Shea, was charted to evaluate the degree to which the technology base can support the decision to transition the NASP into Phase III, detailed design, fabrication, and flight test of the selected configuration. As you will note from Dr. Shea's forwarding letter, the Task Force completed its review during the summer of 1987.

Since the completion of the review, the results have been briefed extensively within the Air Force, DARPA, NASA, and the DoD. Dr. Shea briefed both you and your predecessor. You may know that, in some circles, the findings were viewed as being critical of the program. I can assure you, however, that the Task Force was, and is, committed to strengthening the program.

Publication of the final report has been delayed for a number of reasons, principally related to its public releasability. An entire appendix of the report, alleged to be competition-sensitive, is omitted from this version, so that it may be cleared for wide dissemination.

I share Dr. Shea's conviction that the NASP is a vitally important national program, and that the program is stronger today than when his Task Force undertook its review.

Robert R. Everett
Chairman

Attachment

OFFICE OF THE SECRETARY OF DEFENSE
WASHINGTON, D.C. 20301-3140

DEFENSE SCIENCE BOARD

April 25, 1988

Mr. Robert R. Everett
Chairman
Defense Science Board

Dear Mr. Chairman,

I am pleased to submit to you the final report of the Defense Science Board Task Force on the National Aerospace Plane (NASP). The Task Force was charted to evaluate the degree to which the technology base can support the decision to transition the NASP into Phase III, detailed design, fabrication, and flight test of the selected configuration. Our review began early in 1987 and was basically complete by the summer of that year.

The technology efforts supporting the NASP are funded through a Technical Maturation Program (TMP) which was initiated late in 1986. The technologies critical to NASP are hypersonic aerodynamics, propulsion, structures, materials, guidance and control, and computational fluid dynamics. We reviewed the TMP and related contractor efforts in these disciplines.

We found that, although the Technical Maturation Program was a good start, it fell far short of what would have been required to enter Phase III on the then existing schedule with any acceptable degree of risk. More importantly, major technology issues in all disciplines were not being addressed.

As a major national program, NASP should be planned realistically. We believe that the level of technical uncertainty is too high to commit to schedule or cost at this time.

We recommend that quantitative technical milestones be established for all critical technology needs. Transition to Phase III should occur when these milestones are met. During the present phase, NASP should be a milestone driven program, not an event driven program. The funding balance within the NASP should be adjusted so that the TMP can support these milestones.

In addition to our technical review, and not part of the Terms of Reference, I am compelled to point out that the concept of heavy cost sharing by the contractors is not realistic. The near term business potential to be derived from the program is not large enough to invite corporate investment in competition with other opportunities that have a more assured payback.

The Task Force members were exceptionally well qualified, with University, industry, and ex-government experience in program management and the technologies related to NASP. The Task Force strongly supports the goals of the program because of the major potential benefits to space launch vehicles, projection of military presence anywhere in the world in a matter of hours, and to commercial air transport.

The Phase III NASP design will be an experimental airplane to explore the hypersonic flight envelope, not a prototype of any mission-oriented vehicle.

The results of this study have been briefed extensively within the Air Force, NASA and DoD. I believe our recommendations have been accepted, and the program today appears to be more soundly planned than when we started our efforts.

Sincerely,

Joseph F. Shea

Report of the Defense Science Board Task Force on the NATIONAL AEROSPACE PLANE (NASP)

Dr. Joseph F. Shea
Chairman

TABLE OF CONTENTS

SUMMARY

The NASP started in 1984 as a ~~DARPA~~ Program to explore hypersonic air breathing propulsion. It transitioned during 1985 to a program with the dual goals of demonstrating single stage to orbit and hypersonic cruise with the same vehicle. When President Reagan included the NASP in his 1986 State of the Union Message, it became a major national program.

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Early estimates of vehicle size, performance, cost and schedule were extremely optimistic. Hypersonic technology had been dormant in the United States for over a decade. It took about a year for both Government and Industry to recognize the technical deficiencies which existed in all the critical technologies, and the lack of ground test facilities to explore the hypersonic environment. Late in 1985, DARPA formed a committee, chaired by Dr. Victor Reis, to review technical and management issues on the program. Among their recommendations was the initiation of a Technology Maturation Program (TMP) to better integrate technology efforts with the design program and to address the most critical technical gaps. Implementation began early in 1987.

This Defense Science Board Task Force was chartered in late 1986 to review the sufficiency of the TMP to support a decision to proceed with detailed design and fabrication of a flight test vehicle by the end of 1989.

When our review began, the program was supported by five airframe and three engine contractors doing Phase 2, Part II configuration studies. The Technology Maturation Program brought in additional contractors

and Government Laboratories for specific tasks, and was supplemented by contractor Independent Research and Development efforts.

Late in the Summer of 1987, the planned down select to three airframe and two engine contractors occurred. The program is now in Phase 2, Part II, tentatively scheduled to complete during 1990, at which time one contractor would enter Phase 3 detailed design, fabrication and flight test of the flight test article.

The National Aerospace Plane Program today is significantly different from that envisioned at its outset in 1985. Vehicle weight has grown considerably, as have program cost estimates. Schedules continue to lengthen because of both technical and budgetary issues. We believe more such change can be expected.

The Task Force held four meetings in which the overall program and the Technology Maturation Program were reviewed, four sub-panel meetings on specific technologies and one three day meeting with the contractors. Several of the members have had extensive involvement with the NASP either through membership on the Reis Panel or through consulting assignments directly from NASA or the Air Force.

The recommendations from the Task Force members are unanimous.

Basically, we believe that, as a significant national program, the NASP should be realistically presented to its sponsors within DoD, its supporters in Congress and ultimately, through the White House to the American public. We define "realistic" as a program with a reasonable chance (above 75%, to choose an arbitrary measure) of meeting the performance, schedule and cost goals projected by its proponents. In today's budgetary environment, lack of realism which leads to significant overruns or performance shortfalls can result in loss of program support, and the national embarrassment of a major technical effort poorly executed.

Having looked in some depth into the technologies of importance to the NASP, we are impressed with the progress being made. But we are even more impressed by what has yet to be done to reduce the remaining uncertainties to a reasonably manageable level.

Until these uncertainties are reduced, the NASP should not be a schedule driven program. Rather, it should be paced by events. In particular, we recommend that a set of technical milestones be established which must be demonstrated before a configuration is baselined and Phase 3 detailed design, fabrication, and flight test initiated.

The following sections summarize the Task Force charter and our response to the terms of reference, the major areas of technical concerns, the concerns expressed by the contractors and our conclusions and detailed recommendations. Six appendices

discuss the critical technologies in more detail. The seventh appendix summarizes individual contractor comments.

The Task Force strongly supports the overall goals for the National Aerospace Plane Program. We believe our recommendations suggest a realistic path by which those goals can be achieved.

During the period of our review, the program has continued to evolve. This report contains our interpretation of data gathered January-June 1987 and reflects NASP program status and information current as of that time. We believe management has already begun to respond to the recommendations of the Task Force which have been extensively briefed to DARPA, The Air Force, NASA and DoD.

TERMS OF REFERENCE

The Task Force was chartered to address, but not be limited to, the following issues:

1) The overall sufficiency of the Program's Technology Maturation Plan (TMP).

2) The degree to which the overall program effort adequately supports the achievemant of the technical objectives of Phase 2 of the NASP Program.

3) The need for additional technology development efforts which would extend beyond the time frame of the Phase 2 program.

4) The adequacy and viability of criteria to be satisfied in order to justify a decision to proceed to Phase 3 of the NASP Program.

5) The range of missions for the NASP and variants to the degree required to identify technology issues. New capabilities provided by the NASP which offer the potential for new mission possibilities.

RESPONSE TO ISSUES POSED

Detailed conclusions and recommendations are presented in later sections. This section summarizes the Task Force response to the issues raised in our terms of reference.

1) Although the Technology Maturation Plan is a good start, it is far short of what will be required to enable the NASP Program to enter Phase 3 on the present schedule with any degree of acceptable technical risk.

2) The TMP does not adequately support the objectives of Phase 2. Some tasks provide data too late to help in the configuration decisions which are required to start Phase 3. More importantly, major technology issues in structures and materials, propulsion, aerodynamics, controls, validation of computational aerodynamic codes and ground testing are not being addressed.

3) To close the risks in the areas indicated above, funding of the Technology Maturation Program should be increased. We estimate that twice as much as presently planned could usefully be invested. Since total program funding is unlikely to increase, this means that the configuration efforts in airframe and propulsion should be scaled back to a level sufficient to provide a focus for the technology effort.

4) No quantitative criteria have been established to justify a decision to proceed to Phase 3 of the program.

5) The Task Force did not review the range of missions for NASP. Such studies are still in an embryonic state. However the Task Force members believe that the NASP is a vitally important national program because of the missions, both military and commercial, it will enable, and the technology which will be matured.

Hypersonic, air breathing propulsion can attain a Specific Impulse approaching 2000 seconds, compared to about 460 seconds for conventional high energy cryogenic fuel rocket engines. A single stage to orbit, reusable air breathing vehicle is a possibility for low cost to orbit transportation.

Hypersonic cruise vehicles will enable our Military to project American presence anywhere in the world within a few hours, providing timely response for crisis intervention, strategic reconnaissance and terrorist attack. Civilian hypersonic transports will further shrink the world.

The National Aerospace Plane is a necessary precursor to these three classes of vehicles. As an X-airplane it will explore the realm of hypersonic flight, gathering the data necessary to overcome the limitations of analysis and ground test facilities. Of equal importance, the NASP will provide a focus for the development of the six technologies critical to hypersonic vehicle design, aerodynamics, supersonic mixing and fuel-air combustion, high temperature materials, cooled structures, control systems and computational fluid dynamics.

The following sections address the technical concerns encountered in our review.

DISCUSSION

The technologies critical to the NASP are aerodynamics, propulsion, materials, structures, controls and computational fluid dynamics (which must support several of the disciplines).

The recommendations of the Task Force are based on review of these technologies and the technical and management experience of the Task Force members. This section summarizes the major concerns which shaped our recommendations.

The appendices contain more detailed discussion of each area.

Aerodynamics

The NASP requires an unprecedented degree of integration of the airframe with the propulsion system. Although this is well recognized by program management and the contractors, the problems of integration are formidable. Because of a lack of adequate ground test facilities above about Mach 10, some of the critical design issues may only be resolved by flight test of the vehicle.

The largest uncertainty is the location of the point of transition from laminar to turbulent flow. Estimates range from 20% to 80% along the body span. That degree of uncertainty significantly affects the flow conditions at the engine inlet, aerodynamic heat transfer to the structure and skin friction. These in turn affect estimates of engine performance, structural heating and drag. The assumption made for the point of transition can affect the design vehicle gross take off weight by a factor of two or more.

Computational fluid dynamics cannot predict transition because turbulence must be introduced into the calculations empirically, and no relevant data base exists for the high mach number flight regime. In addition, while CFD is reasonably accurate for two dimensional laminar flows, calculations of three dimensional flow around structural details usually needs to be calibrated by experimental data. Therefore estimates of local heating conditions will be imprecise.

Historically, calculations of aerodynamic performance have been validated in ground test facilities. For Mach numbers between ten and twenty five no ground test facilities exist which can produce true stagnation enthalpy and full scale Reynolds numbers. One or several of the critical parameters can be simulated separately in existing or proposed facilities, and these will provide useful data which may narrow the uncertainties. However there is currently no way to validate methods for combining such partial simulation results to represent the true flight environment.

The uncertainties of aerodynamic performance will affect all aspects of the NASP design.

The NASP program has initiated a major analytic and experimental effort to understand the nature of transition. It would seem prudent to delay initiation of detailed vehicle design until that effort has narrowed the uncertainty in location of the transition point to an acceptable tolerance.

The air breathing propulsion system for the NASP must operate from a standing start to Mach 25. It will consist of three distinct cycles, low speed (up to about Mach 1), ram jet (subsonic combustion), and scram jet (supersonic combustion).

The low speed cycle is a significant design challenge, but can be adequately tested in ground facilities and independent flight, as can the ram jet. Transition from ram jet to scram jet could be the most critical stage of flight, when a normal shock must be forced through the diffuser, combustor and nozzle without flameout or loss of thrust so that the vehicle can continue to accelerate. The system must avoid any strong shock waves that might be caused by fuel injection or details of the variable geometry in the engine flow path required to optimize performance over the wide flight regime. Unwanted shocks could destroy performance or cause unstart which could place heavy demands on the vehicle attitude control system.

Very little is presently known about the mixing and combustion of hydrogen at very high supersonic velocities. It is possible that some of the reactions will not be completed in the combustion chamber, or even in the nozzle, which would result in a loss of performance. Fundamental research in this area has been proceeding slowly because of computational and experimental limitations.

Calculations of flow through the engine will have larger uncertainties than those discussed for aerodynamics because of the uncertainty in inlet conditions, the more complex geometry of the flow path and the introduction of combustion kinetics. Ground test facilities will not provide data much above Mach 8, and full scale testing will probably not exceed Mach 4. Valid testing at higher Mach number will only be done by expanding the flight envelope of the full scale vehicle. It is highly likely that flow anomalies will be encountered in the propulsion system which will require redesign before the flight test program can proceed. Non intrusive instrumentation which can provide the data to resolve such problems must be developed.

The NASP program should consider conducting the equivalent of a limited pre-flight readiness test (PFRT) for the NASP propulsion system, as is conventional practice for a manned aircraft program. This would require a ground test facility with continuously variable Mach capability to as high a velocity as practical. Ability to demonstrate ram jet to scram jet transition would be very desirable. To this end, modification of the Aeropropulsion Systems Test Facility (ASTF) tunnel at Tullahoma, Tennessee should be studied.

Materials

Based upon the preliminary design and performance estimates presented to the Task Force, surface temperatures of the NASP structure will range from in excess of 3000°F to less than 1200°F. For a typical configuration, some 15% of the wetted

area might be exposed to temperatures above 2600°F, 20% to temperatures between 1800°F and 2600°F, about 50% to temperatures between 1200°F and 1800°F, with only 15% below 1200°F where "conventional" materials are available. The higher temperature requirements force the vehicle designer to make a choice between new, promising materials which are in various stages of advanced development (in general, available only in laboratory quantities), or active cooling of a major fraction of the structure.

There appeared to be a discrepancy between consideration of the advanced materials for the high temperature structure and the availability of such material on a schedule compatible with vehicle fabrication. Development of new materials including scaled up production facilities is estimated to take twelve to fifteen years. At the time of our review, the NASP program schedule would have allowed only five to seven years. We also noted that no funds were programmed to facilitate whatever scale up is finally required, although the new materials would not see immediate demand outside the NASP Program and therefore would not be likely to attract private investment.

The lack of scaled up production processes also affects the quality of the material characterization data available to the structural designer. Small quantity lots will not provide the range of material properties required to establish design allowables, damage tolerance and fatigue characteristics for production materials.

The NASP structure will be exposed to high temperature, high enthalpy, disassociated gas. Reusable coatings will be essential to protect the materials.

In areas where the structure is exposed to hydrogen at high temperature and pressure (such as active cooling channels), the hydrogen molecules can penetrate the material and cause embrittlement. The problem is not well understood. The program is raising contractor awareness of the problem, but no funded effort was underway at the time of our review.

It is the opinion of the Task Force that availability of suitable materials in production quantities will be the pacing element in the NASP schedule, and that resources must be identified to fund the necessary scale up and characterization effort.

Structure

The structural designer has the fundamental task of designing an optimum structure to acceptable minimum margins of safety commensurate with man rating the NASP. To do that requires that:

1) The materials to be used must be fully characterized from material reasonably close to or in production, not from small laboratory samples.

2) The complete operating environment must be reasonably known.

3) The analysis methodology to determine external loads and derive therefrom internal loads must be available, verifiable, accurate and reasonably efficient.

4) The design can be verified through adequate ground and flight test.

Because of the uncertainties noted in earlier sections in aerodynamic loads and heating, materials availability, precision of computation and lack of ground test facilities to replicate thermal and structural flight loads, the current ability to meet the structural designers requirements are marginal to non existent.

To achieve the NASP performance goals, the vehicle structural weight fraction will have to be twenty five to thirty per cent less than the Shuttle.

In most conventional aircraft the prime loads are aeroelastic. Environmental loads (thermal, acoustic, dynamic response) may be critical locally, but are not usually coincident with the critical aero loads and are normally analyzed as separate design conditions. But for the NASP the loading is aero thermal elastic acoustic and is coincident at the critical design conditions. Achieving the required structural mass fraction in the face of existing computational capability and uncertainties in the load and material data bases is problematic.

Effort must also be directed at fabrication methods for the new materials. Fastening poses a particular problem because some of the materials demonstrate extreme brittleness in certain temperature ranges, as well as a negative coefficient of thermal expansion.

Because of the lack of structural test facilities, adequate instrumentation with real time data transmission will be a flight safety requirement. Transmission through the plasma sheath which will envelope the vehicle at the higher Mach numbers presents a severe challenge.

The Task Force believes it would be prudent to establish technical milestones to develop the data bases required for structural design with acceptable tolerances and refine analytic methods. These milestones should be accomplished before proceeding with detailed design.

Controls

The National Aerospace Plane (NASP) Program has some of the most demanding design problems of any flight vehicle development program to date. The extent of coupling between the NASP control system and the vehicle airframe/propulsion system requires that they evolve simultaneously. The degree of uncertainty regarding available component technology and associated performance complicates the task of control system development and mandates early identification of principal design sensitivities and trades. Also, uncertainties regarding environment characteristics demand development of control strategies which maximize available adaptability and authority and minimize the adverse influence of hostile environment effects. All these considerations are as applicable for development and testing of a research vehicle as for an operational system. Less specific knowledge of the environment during early test flights may actually demand more control system adaptability.

To successfully develop the NASP control system, it is necessary to identify the most significant design concerns involving vehicle control and to initiate a technology development plan capable of addressing the issues. The effort should occur early enough to influence overall vehicle design in a manner that will assure successful vehicle and control system integration.

T' ↄ issues which must be addressed include:

- attitude control (with accuracy to, perhaps, 0.1 degrees while the vehicle undergoes thermoelastic deformation).
- trajectory optimization
- propulsion optimization, including algorithms and sensors to control both throttle and variable geometry
- stability and control with large uncertainties
- sensors and instruments for the high Mach number regime
- handling qualities
- abort scenarios
- integrated guidance and control system

Most of these issues are vehicle design dependent. Therefore, a satisfactory vehicle design cannot be developed independent of the on board control system.

The Task Force found the technology road map developed by the flight systems working group has the elements described to provide an adequate understanding and effective development program for NASP. However, it is not being adequately funded. Controls and flight dynamics optimizations can relieve environments inimical to successful realization of key but very uncertain technologies involved with structures, structural materials, and propulsion systems, for instance. At the levels of program funding currently applied to the flight systems technologies, it is doubtful that these optimizations can be examined adequately and that alternatives will be available on a schedule compatible with the air frame/ propulsion developments. As a rough example of the disparity, it now appears that approximately 1 to 2% of the currently identified funding in the program is intended to cover this functional area. It is our experience for aerospace vehicles that avionics represent a much larger per cent of the total value of the vehicle. It will not be possible to reach the goals of the program at the level of funding now allocated to the controls and guidance functions.

Computational Fluid Dynamics

The preceding sections highlighted the question of the accuracy of the CFD codes. Much progress has been made in this discipline in recent years, but there is still a long way to go, particularly at the higher Mach numbers. The Task Force found that the CFD team had a realistic view of the limitations of their calculations, and a

well thought out plan for improved capability. However the program must guard against exaggerated claims about the efficacy of CFD as a substitute for wind tunnel or flight test data. If expectations are raised too high too soon, CFD could be put in the unfortunate position of losing credibility when, in fact, the community will have been making significant advances that should be recognized as such.

Today, two dimensional calculations are good; three dimensional capability is evolving. But even where the codes are good, they must be calibrated and validated from real world data. This arises from the need to insert certain empirical data such as the onset and length of the transition to turbulence and turbulence characteristic length. In Mach and Reynolds number regimes where no data, or incomplete data exist, the calculations will be precise but not necessarily accurate. The calculations are also strained when all relevant parameters, such as combustion kinetics, must be included.

CFD is essential to the NASP program. But it must be recognized that the accuracy attainable over the next few years will fall short of what is required for vehicle design and performance estimates.

Another potential problem is the computational requirements. Some of the codes take a long time on a powerful computer to converge, on the order of 24 hours. It is likely that several thousand such runs will be required to design the vehicle. Measures should be taken to assure that computer resources will be available, as well as effort directed at reducing execution time.

CONTRACTOR RESPONSE

The Task Force met with all eight contractors to review their technology efforts and explore their views of the issues critical to the program. Each meeting lasted approximately three hours, thirty minutes of which was a private session with the Task Force.

The following paragraphs summarize the observations and concerns common to most of the eight discussions. (The meetings occurred in late June, 1987, and reflect perceptions of the program at that time).

- The NASP is truly an experimental vehicle, not a prototype of a space booster or a hypersonic cruise airplane. It will be a success if it achieves high Mach number flight. Design iterations may well be required before orbital insertion is achieved.

- There is little confidence that the aero-breathing propulsion alone will be sufficient to gain orbit in the early phases of the program.

- There are approaches to compensate for the uncertainties in the aero-breathing propulsion, e.g. rockets to help achieve orbital velocity and/or very low drag designs.

- Uncertainties in aerodynamic data, particularly as they affect temperature estimates and propulsion performance, drive the vehicle configuration. Estimates of gross take off weight range

from about 300,000 pounds to 500,000 pounds. Confidence in these numbers is not yet high.

- Materials development and manufacturability pace the program. Materials characterization and scale up for production are not adequately funded. The time required for these efforts is too long to support the (then) existing Phase 3 schedule.

- The Technology Maturation Program is a good start, but is not sufficiently focused on the requirements of the most probable configurations. Although information exchange is good, stronger contractor participation in defining the program might help.

- Teaming of airframe and engine contractors would be welcomed. Coordination among several contractors presents a significant burden.

- A variable Mach number wind tunnel is required.

- The (then) scheduled Phase 3 schedule was not realistic.

- The (then) planned Phase 3 funding was not realistic.

The Task Force found these thoughts congruent with our own observations.

CONCLUSIONS

Based on our review of the NASP program which extended over a six month period, the Task Force reached the following conclusions:

(cont'd p. 2)

1) The NASP program goals are valid. The technologies which NASP will develop will make significant contributions to our national military and space capabilities and our civilian economy as we enter the 21st ~~twenty first~~ century.

2) The NASP is truly an X-Vehicle. Expectations of short term operational utility should not be raised.

3) Technical uncertainties in all critical disciplines must be narrowed before detailed design is initiated. Uncertainties are too large to estimate with any degree of accuracy the cost, schedule or performance which can be achieved in Phase 3.

4) Readjust the program funding priorities to favor the Technology Maturation effort, while retaining sufficient effort in definition airframe and propulsion configuration to provide focus for the technology work.

5) An experimental program of this type should be event driven, not schedule driven. Demonstration of quantitative technical milestones in all critical disciplines should pace the program. (edc)

6) Hypersonic flight will be important to the United States in the decades ahead. Adequate national ground test facilities must ultimately be provided.

RECOMMENDATIONS

These findings lead the Task Force to make the following recommendations:

1) Maintain the present program objectives. A manned hypersonic vehicle, with the potential of demonstrating a single stage to orbit and extended hypersonic cruise, provides challenging focus for the development of the critical technologies.

2) Complete a rigorous risk identification and closure analysis. Identify the funding, schedule and technical resources required to reduce the risks to a level commensurate with the experimental nature of the vehicle.

3) Establish a quantitative set of technical milestones in all critical disciplines which must be demonstrated before entering Phase 3.

4) In anticipation of the results of the risk closure analysis, begin now to replan the program by making the start of Phase 3 dependent upon demonstration of the technical milestones and by significantly increasing the portion of program funding devoted to maturing the technology.

5) Emphasize the experimental nature of the program. Once flight test begins, several design iterations may be expected before orbital insertion is achieved. Program planning should anticipate the resources which will be required.

6) Proceed with the planned down select for both engine and airframe contractors. To reduce the number of design combinations which must be considered, team airframe and engine contractors at an early date.

7) Focus the Technology Maturation Program to support the selected configurations. Strengthen the contractor's input to the definition of Technology Maturation Tasks.

8) Develop a plan to man rate the air breathing engine. Investigate the addition of a variable Mach number nozzle to the Aeropropulsion Systems Test Facility tunnel at Arnold Engineering Development Center to provide a ground test propulsion facility.

9) NASA and DoD should study the possibilities for national hypersonic test facilities for aero-thermal, propulsion and structures.

10) Materials availability will be a pacing item for the program. Develop a plan to scale up to production quantities for the materials selected and to provide characterization data for structural design.

11) Fund the flight control system technology road map tasks to a level commensurate with the importance of integrated flight controls to the program.

12) Continue strong support to CFD validation and the narrowing of the uncertainty in location of the point of transition to turbulence.

13) Identify the computational resources which will be required to support the detailed design phases of the NASP.

We have refrained from making detailed recommendations in each of the technology areas in the belief that the risk closure analysis recommended above will provide the definitive plan required for the program.

15

THE UNDER SECRETARY OF DEFENSE

WASHINGTON, DC 20301

ACQUISITION

12 DEC 1985

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference--Defense Science Board Task Force on the National Aerospace Plane (NASP) Program

You are requested to organize a Defense Science Board Task Force to review the National Aerospace Plane (NASP) concept, technical basis, program content and missions.

The NASP is a joint Department of Defense/National Aeronautics and Space Administration research program directed towards an entire new generation of aerospace vehicles. The specific objective of the program is to develop, and then demonstrate in an experimental flight vehicle, the technology which will enable the Nation to develop both military and civil aircraft capable of sustained hypersonic flight within the atmosphere and space launch vehicles capable of delivering payloads into orbit at greatly reduced costs. The NASP is envisioned as an airbreathing, liquid hydrogen-fueled, horizontal takeoff-and-landing vehicle with single-stage-to-orbit capability.

During the past decade substantial progress has been made in hypersonic airbreathing propulsion, advanced materials and structures, and computational technologies leading to a consensus that hypersonic, transatmospheric vehicles may be technically feasible around the turn of the century. Proof of that feasibility will rest on the development of an adequate data base supporting the individual and integrated disciplines of propulsion, structures, avionics and aerodynamics. The NASP Program is designed to provide that data.

During the next thirty-six months a joint DOD/NASA team led by the Defense Advanced Research Projects Agency will be conducting the Technology Development and Assessment Phase of the Program, Phase II. The principal challenge facing the team is the integration of the individual technology investigations with the major contracted efforts in propulsion module design and fabrication and in vehicle design and component development.

The issues that the Task Force should address include, but are not limited to:

1. The overall sufficiency of the Program's Technology Maturation Plan (TMP).

2. The degree to which the overall program effort adequately supports the achievement of the technical objectives of Phase II of the NASP Program.

3. The need for additional technology development efforts which would extend beyond the time frame of the Phase II program.

4. The adequacy and viability of criteria to be satisfied in order to justify a decision to proceed to Phase III of the NASP program.

5. The range of missions for the NASP and variants to the degree required to identify technology issues. New capabilities provided by the NASP offer the potential for new mission possibilities.

The Assistant Secretary of Defense (Research and Technology)/Director, DARPA, Dr. R. C. Duncan, will sponsor the Task Force and Dr. Joseph Shea will serve as Chairman. Dr. Craig Fields will be the Executive Secretary, and Colonel D. Fang, USA, will be the DSB Secretariat Representative. It is not anticipated that your inquiry will need to go into any "particular matters" within the meaning of Section 208 of Title 18, U.S. Code.

MEMBERSHIP OF DSB TASK FORCE ON
NATIONAL AEROSPACE PLANE (NASP)

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Dr. Joseph F. Shea*
Raytheon Company

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Textron, Inc.

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Princeton University

Professor Eugene E. Covert
Center for Aerodynamic Studies
Massachusetts Institute of Technology

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Institute for Defense Analysis

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BASLE Corporation

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Private Consultant

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Private Consultant

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VADM Ernest Richard Seymour, USN (Ret.)
ERS, Inc.

Government Advisors

Army
Mr. Thomas Daniels
Office of the Assistant Secretary of the Army
(Research, Development, and Acquisition)

Navy
RADM Robert H. Shumaker
Surface and Electronic Warfare Development Division

Air Force
Brig Gen Thomas W. Honeywill
Office of the Deputy Chief of Staff
for Research, Development, and Logistics, HQ USAF

OJCS
Maj Dale E. Tietz, USAF

Strategic Defense Initiative Organization
Dr. Gordon Smith

National Aeronautics and Space Administration
Dr. Raymond S. Colladay

Executive Secretary

Dr. Craig I. Fields
Defense Advanced Research Projects Agency

DSB Secretariat Representatives

COL Donald R. Fang, USA
COL Robert Bruce, USA

APPENDIX A

Aerodynamics

Configuration

The configuration selected for the NASP Demonstration prototype will not necessarily represent any particular application and will certainly not represent the optimum configuration for any of the several objective applications stated for the program:

1) Low-cost payload space launch vehicle

2) Hypersonic transport

3) Quick-reaction orbit and return military vehicle

Therefore the NASP will be an experimental aircraft to explore new regimes of flight especially with respect to air-breathing propulsion and its interactions with the airflow around the vehicle.

As an aerodynamic test vehicle, the NASP will be analogous to the X-1, X-2 and X-15 which pushed manned flight through the speed of sound and up to Mach 6 and not analogous to the X-29 (forward-swept wing) which demonstrated a specific aircraft configuration and design concept. On the other hand the test of the scram jet propulsion system of the NASP is more nearly a design/configuration related prototype of possible future operational system hardware.

The main problem in the design of aircraft for sustained flight at hypersonic speed up to orbital or near orbital velocities (Mach 20) lies in providing a propulsion system capable of giving sufficient

thrust per unit of engine weight and volume and sufficiently high specific impulse, I_{sp}, to meet the desired range (semi-global) for a transport, or Δv, (30-35,000 f.p.s.) for an orbital vehicle, with a vehicle of minimal lift-off weight. With (non-nuclear) rocket propulsion, the highest achieved lox-hydrogen I_{sp} is 460 and in terms of theoretical and practical limits this is considered not to be capable of much extension with conventional fuels and oxidizers. In order to achieve high thrust (ruling out such systems such as electric and ionic propulsion) I_{sp}'s in the range of 1000-3000 which are needed to meet the most demanding of the mission objectives over the flight regimes up to Mach 25+ in a <u>single stage vehicle</u>, air-breathing propulsion is called for.

Conventional turbojet, turbofan, ram jet suffer excessive inlet losses as Mach numbers of 6 are approached and also have problems in heat addition to air already at extremely high--near stagnation--temperatures. Thus, the propulsion system of choice for high hypersonic flight conditions is the supersonic combustion ram jet in which the flow remains supersonic in its passage through the propulsion system.

Given the scram jet propulsion installation and integration, the air vehicle configurations being favored are relatively conventional and in many ways simply an extension of the well known body-delta wing configuration used in many supersonic designs.

<u>Boundary Layer Transition</u>

A major aerodynamic problem in design and performance assessment of the NASP is that of determining the location of the region of

transition of the boundary layer from laminar to turbulent flow. Transition location has profound effects not only on the drag and other aerodynamic forces on the air vehicle but also on the engine inlet flow which can have major impact on propulsive efficiency. The scram jet thrust is particularly sensitive to inlet kinetic energy efficiency. Also heat transfer rate rises severly in transition from laminar to turbulent flow and thereby also affects the structure and the fuel flow rates required for structural cooling, thereby having marked effects on vehicle weight.

For complex geometries, the transition point location is often difficult to pin down even in subsonic and supersonic flow, but a vast quantity of empirical data and approximate and semi-empirical analysis methods exist. Experienced aerodynamicists using these data and methods can usually make valid judgments for design in lower speed flows. For the hypersonic Mach number ranges, most important for the NASP, there is not a substantial data base and only partly validated analysis methodology. In view of the potential impact of uncertainties in the transition location, this is by far the single area of greatest technical risk in the aerodynamics of the NASP program.

Propulsion System Integration

The supersonic combustion ram jet by its very nature requires an unprecedented degree of integration of the aerodynamic design of the airframe with the engine installation. Thus, the entire nose of the aircraft forms part of the inlet and the entire aft end of aircraft can behave, in effect, as part of the exhaust nozzle. This is well recognized by the program managers and the contractors

in the NASP program and a high degree of overlap between the analysis, design, and test activities of airframe and engine contractors is being maintained. Nevertheless the problems of integration are formidable and many critical issues in aerodynamics and propulsion technology remain to be resolved.

If some of the uncertainties bearing on the thrust of the engine and the drag of the airframe cannot be sufficiently narrowed, there is the possibility that for any given vehicle a "hypersonic speed-barrier" (much like the "sonic barrier" of the immediate post-war period) may be encountered.

Experimental Facilities

The problems of estimating such a fundamental performance measure as the thrust versus drag at high Mach numbers are compounded by two main factors. One is the high degree of interaction of the airframe and propulsion system and the other is the lack of ground test facilities capable of simultaneously simulating all of the important parameters of hypersonic flight particularly in the M=10 to M=25 range. Computational fluid dynamics (CFD) is being heavily relied on in the program to resolve many of the aerodynamics and propulsion problems in this Mach number range. However, validation of the empirical components (e.g., turbulence models in "real" gas flow) for M=10-25 with true stagnation enthalpy and full scale Reynolds number cannot be accomplished in any existing or proposed ground test facility. One or several of these parameters can be simulated separately in a number of facilities but there is currently no way to validate methods for combining such partial simulation results to represent the true flight environment.

Flight test data which are available for validating CFD codes from the Shuttle and ballistic missile reentry data, as well as from the ASSET and PRIME flight test programs, probably represent the closest simulation conditions for combined parameter sets. For various reasons, mainly differing flight corridors, fundamental configuration differences, and scale, none of these flight data completely represent some of the most critical high Mach number points for NASP flight profiles. If, after more detailed accumulation and analyses of data from ground facilities in relation to the existing flight data, significant gaps in understanding and discrepancies are found to exist, and if these bear on particular aerodynamics/propulsion performance sensitivities of the NASP vehicle, serious consideration should be given to undertaking additional unmanned model flight tests in support of the NASP program. Particular attention should be given to problems of engine inlets and exhaust flow interactions with the airframe since none of the previous flight tests in the high hypersonic regime (Shuttle, ASSET, PRIME, and RV's) involved air-breathing propulsion specific parameters peculiar to inlets and exhausts.

APPENDIX B

NASP Propulsion

Summary

The purpose of this appendix is to describe some of the critical issues involved in the design and development of NASP propulsion and then, keeping these issues in mind, to comment on the technology maturation program which is to provide the data and tools required for their resolution.

Our examination of the propulsion technology maturation program indicates that it is not likely to have a timely influence on the presently scheduled NASP design and development process. To decrease the development risks, we recommend that greater emphasis be placed on the propulsion technology maturation program, giving serious consideration to the possible need for fully integrated engine tests in a variable Mach number wind tunnel.

Design and Development Issues

A) Low Speed Propulsion

NASP is conceived as propelled over most of its flight regime by a ram jet and scram jet which are to accelerate it to orbital velocities. Neither ram jets, nor scram jets are capable of producing any thrust at standstill. For this reason the NASP propulsion must involve, in addition to the ram jet and scram jet, one other propulsive system capable of providing the take-off thrust and acceleration through the high drag, transonic region. For this purpose conventional

turbojets, rockets, air-turborockets, and ejector-rockets are are all being considered. Of these only the turbojets and rockets are ready for use, the others remain to be developed.

Regardless of which will eventually be chosen, it is clear that the selected system will, by adding weight, reduce the payload that would be obtainable if such a system would not be necessary. Therefore one important criterion for selection must be minimum additional weight. Furthermore this additional, low-speed system will have to be integrated into the ram jet and scram jet configurations with a minimum detriment to their performance and, also, when inactive, will have to be protected from the effects of the very high heat generated within the engine. The capability to design a detriment-free integration into the ram jet and scram jet configurations is, at present, not well in hand. This because the assessment of the flow perturbations created within the ram jet and scram jet by the low speed system is likely to be difficult to analyze and may require very many, lengthy, three-dimensional fluid dynamics computations and/or extensive developmental testing.

B) <u>Ram Jet Propulsion</u>

All of the options for a low speed propulsion system discussed above become less efficient than the ram jet at about Mach number 3. Indeed for higher speeds some require special devices (such as inlet air pre-coolers) to operate at all. But the scram jet becomes more efficient than the ram jet somewhere between Mach numbers 6 and 8. For this reason the ram jet

serves as an intermediate propulsion system during the transition between the low speed and the scram jet propulsion. While the ram jet is very similar to the scram jet, and should relatively easily fit within the scram jet envelope, its conversion to supersonic burning requires a solution to many difficult design and development problems for which, at present, relevant design data is unavailable. For example during such a conversion, while the vehicle continues to accelerate, a normal shock must be forced to pass through the diffuser, combustor and nozzle without flameout or loss of thrust. The data relevant to the understanding of the intricacies and control of such a process is currently lacking and probably will have to be obtained in a variable Mach number wind tunnel. Similar data is also needed for the conversion from low speed to ram jet operation.

C) Scram Jet Propulsion

1) Avoidance of Strong Shocks

In the scram jet one must not allow any strong shocks to form because such shocks, when occurring during high flight speeds, would severely affect its performance. The avoidance of strong shocks anywhere inside the engine is difficult to accomplish because, for efficient heat addition, the fuel must be homogeneously distributed by injection within the air stream and this may require insertion of nozzles, flame holders, etc. which by blocking the flow, may trigger the unwanted shocks. Such unwanted shocks may also be created inside the diffuser, particularly at off-design conditions,

when the shock configuration does not properly match the engine inlet contours usually triggering undesirable, strong, local, adverse pressure gradients which may separate the boundary layer. In addition, as already mentioned, the integration of the low-speed and intermediate propulsion systems with the scram jet may result in a configuration conducive to the creation of strong shocks. Since such shocks may also be caused by the interactions between engine components, and the external flow, it is important to have a detailed understanding of three-dimensional flow at all times inside and outside the complete engine. Such understanding is presently lacking.

2) Regenerative Cooling

The very high speeds at which NASP will operate within the atmosphere are capable of creating very high wall temperatures at which materials suitable for NASP construction lose their structural integrity. To prevent this from happening it is proposed to cool critical (or selected) external and internal NASP surfaces regeneratively, utilizing the very high heat capacity of liquid hydrogen. To design such a system requires a good understanding of heat transfer processes both outside and inside the engine. However the estimation of the external heat transfer at high speeds is hampered by inadequate knowledge of boundary layer transition and the estimate of internal heat transfer is similarly hampered by inadequate understanding of supersonic burning. In addition, since the ram jet and scram jet must continuously vary

their configurations with the every increasing flight velocity, the design of the regenerative cooling for such continuously adjustable surfaces will be very complex. Complex designs need thorough experimental verification. Thus fundamental research into issues such as shock-on-shock or corner heat transfer and extensive developmental testing will be required to produce a satisfactory design of the regenerative cooling system.

3) Supersonic Combustion

The very high heating value of hydrogen (51570 Btu./lb. of fuel) and its high cooling capacity make it a very appropriate fuel for scram jets. However very little is presently known about the process of its supersonic combustion at very high velocities. For example one important question which is yet to be answered before the design and development of NASP can be undertaken is: can the expected heat addition to the air stream be carried out in a reasonable combustion chamber length? It is possible that at the very high velocities existing in the combustor some of the reactions will not be completed within the combustion chamber, or even in the nozzle, thus adding less heat to the air flow than expected and producing less than expected performance. Another important question which remains to be answered concerns the stability of the combustion process. Fundamental research into these complex issues has been advancing very slowly because of a lack of appropriate experimental facilities and because of

severe complications that combustion kinetics introduce into the fluid dynamics equations.

D) Terminal Propulsion

For scram jets at high velocities (>18000 ft/sec.) the specific impulse tends to decrease appreciably with increasing flight speed and the drag to thrust ratio tends to increase. Because of this effect scram jets ability to accelerate at high velocities becomes marginal and orbital injection by use of inertial forces instead of thrust is usually not feasible.

To improve the acceleration at flight velocities beyond, say, 18000 ft per second, it is often proposed to add rocket propulsion for the final boost from atmosphere to orbit (a rocket must also be used for deboost from orbit). This of course reduces the effective specific impulse, increases vehicle "dry" weight and, if not done judiciously, may also increase external drag (all along the trajectory and not just at high velocities) or grossly complicate scram jet's internal design and impose additional penalties on its performance.

E) The Testing Problem

1) Low Speed and Supersonic Testing

As already discussed, the development of air-breathing orbital boosters will require a lot more information than is currently

available. Up to Mach 8 such information will have to be obtained in suitably modified ground facilities to allow not only component, but, also, completely integrated engine testing. Such integrated engine testing will be needed to provide the data for design of engine controls and also to verify overall accelerating engine performance. Indeed, it would be desirable to conduct such accelerating engine tests in a suitably modified, variable Mach number, wind tunnel.

2) <u>Hypersonic Testing</u>

At high (>10) Mach numbers even the barest design data required for the development of scram jet engines is at best meager, or completely lacking. Such design data is essential to assure the validity of analytical performance computations. In addition, scram jet engines will have to be fully aerothermodynamically integrated, the details of their mixing and combustion processes well understood, their heat transfer and cooling well manageable, their structural integrity assured, unsteady behavior under control, etc., before they will be considered ready to use. This means that to acquire the needed data in ground facilities one will need tunnels which will simulate not only the Reynolds and Prandtl numbers but also the total enthalpy and total pressure for adequate periods of test time. But such tunnels require tremendous amounts of power, and therefore are not likely ever to be built.

For these reasons the development of scram jet engines

able to operate at Mach >10 must heavily depend on computational fluid dynamics (external and internal), computational aerothermophysics and computational chemistry and chemical kinetics. Although the state of the art of these techniques is, as yet, not sufficiently well developed to depend on them for extensive support of such a development program, great advances in this field are being made very rapidly and we are already able to solve numerically three dimensional, unsteady, compressible laminar and turbulent (but averaged in the Reynolds manner and containing some empirical relations) Navier-Stokes equations with strong viscous-inviscid interaction.

Even the most ardent advocates of computational methods recognize that the risk in the development of engines is so great that the use of proven verification methods by means of tests cannot be abandoned. Since ground facilities for meaningful complete engine testing will not be available, much more emphasis will have to be put on restricted simulations of individual component behavior by limiting test parameters, as appropriate. But even these techniques, though not entirely satisfactory, will probably require new and extensive high speed test facilities.

Completely integrated scram jet engines will have to be tested in flight. But flight testing is inconvenient and often constrained by the ability to transmit large amounts of test data so that rarely is it able to provide as much detailed information as may be gathered on the ground. Furthermore

for scram jets, which will have to be boosted to, say, Mach 7, and will have extensive flight range, the logistics of the testing operations will be difficult and the testing itself very expensive.

Comments On Technology Maturation Program

A) Introduction

As is well known the scope of the air-breathing hypersonic propulsion research has been very limited since the mid-sixties. To fill this void, the propulsion technology maturation program tries to resolve the critical issues and to provide the data base and techniques which will be needed for the design and development of NASP propulsion. The comments and recommendations which we are making here resulted from examination of: (i) the Technology Maturation Plan (Version "A"- December 1986), (ii) the Technology Maturation Task Plans for Propulsion and Computational Fluid Dynamics, (iii) presentations which we received from NASA on February 23-24, 1987 in Cleveland, (iv) presentations by industrial contractors on June 23-25, 1987 in Washington and (v) from a number of discussions held between the Task Force's members.

The Technology Maturation efforts are divided into two overlapping groups: low and high speed propulsion. To more clearly see the relation between the comments and the program we will use the same division in our discussion even if this will cause some repetition.

B) Low Speed Propulsion

1) General Comments

This part of the maturation program addresses critical technology issues from takeoff to ram jet-scram jet transition. Part of the effort is concentrated on the development and verification of computational codes for aerodynamic components such as inlets and nozzles. Some of the effort is also devoted to special system experiments, diffuser and combustor development, thermal management, dynamic modeling, controls and development of suitable instrumentation. Many of the so obtained results should be useful regardless of which of the possible low-speed systems is finally chosen.

2) Combustion Instability

Inlet buzz, inlet unstart and other types of unsteady phenomena are often triggered by the instabilities of the combustion process and for this reason a thorough understanding of this process is essential even for subsonic combustion. The technology maturation program does have tasks which are criented towards code development and verification for subsonic combustion but none of these seem to provide design data on the effect of, say,

unconventional fuel injector shapes (such as may be needed for supersonic burning) on combustion stability. An expansion of effort in this area is recommended.

3) Verification Of Dynamic Modeling

Some of the most difficult problems likely to be encountered by the developers of the propulsion system are those related to internal engine dynamics. To insure that such dynamic behavior does not lead to a loss of thrust, it will have to be sensed and controlled. The Technology Maturation Program does have some tasks devoted to propulsion system dynamic modeling (which is essential to such a control) but these do not seem to be directed at the special problems which will occur during operational transition from the low-speed system to the ram jet and again from the ram jet to the scram jet. Furthermore the codes used for this modeling will be verified in individual component tests and this is hardly adequate. For this reason we recommend that serious consideration be given to the verification of dynamic modeling in extensive ground testing of a complete engine during the periods of conversion from the system providing low-speed propulsion to the ram jet, and from the ram jet to the scram jet. If at all possible such tests should be carried out in a variable Mach number tunnel.

5) Global Performance Codes

The CFD codes capable of handling the complete engine (that is integrated diffuser, combustor and nozzle codes) which are being developed by SAI for the engine contractors are currently two-dimensional. These codes are used to obtain estimates of global engine performance parameters such as kinetic energy efficiency, thrust coefficient, etc. But two-dimensional codes are incapable of handling three-dimensional effects caused by, say, the side walls between adjacent engine passages or by the angles of attack and yaw. For this reason the so estimated engine performance may be in considerable error. Three-dimensional versions of these integrated codes will not be ready for some time.

C) High Speed Propulsion

1) General Comments

This part of the technology maturation program pertains to propulsion issues over a wide range of operating speeds (from M=3.5 to orbital insertion). By covering the range from M=3.5 the program wisely overlaps some of the issues common to ram jets and scram jets thus attempting to find the best conditions for transfer from one to the other. The effort is focused on providing basic data and design methodology for inlets, combustors and nozzles for

the very high speeds at which they will operate. For the Mach 5-8 range two engine test facilities of sufficient scale are being constructed to conduct and support the prime engine contractors' tests. These facilities should be able to furnish much of required overall (but not necessarily basic design) engine data up to Mach 8. However for higher speeds the ground testing is very limited by the conditions that can be duplicated and by the testing time. Thus for higher speeds, ground testing, at best, can offer but meager and incomplete bits of the required information. Therefore much of the basic data for high speed propulsion will have to be obtained by use of computer simulations, many of which cannot, and will not, be fully validated.

2) <u>Boundary Layer Transition</u>

Our present knowledge of transition between the laminar and turbulent boundary layers at hypersonic speeds is very meager. Though some empirical rules exist, their validity has not been satisfactorily tested. But the inlet "cone" for the very high speed scram jet will have to be very slender and long thus causing substantial growth of the boundary layer possibly leading to the laminar-turbulent transition. Such a transition can drastically affect the geometry and heat protection of scram jet inlets and its thorough understanding is therefore

essential to the design and development process. The present program lacks sufficient efforts in this area. We recommend therefore a much greater emphasis on the analytical and experimental studies of transition at high hypersonic speeds including the effects of pressure gradients, real gas composition, cooled walls and three-dimensionality of the flow.

3) <u>Turbulent CFD Codes At High Speed</u>

The CFD codes for turbulent flow consist of Navier-Stokes equations time averaged in the Reynold's manner. At present, to solve such equations it is necessary to use empirical relations instead of the so called Reynold's stresses. These relations need to be validated at the very high velocities. Since the CFD codes will be crucial to the design of NASP we recommend increased emphasis on the validation of CFD codes for turbulent flow at high speeds. Such experimental validation should encompass the effects of pressure gradients, real gas composition, cooled walls, and three-dimensional flow.

4) <u>Supersonic Combustion</u>

As previously explained, the essence of scram jet's superiority over the ram jet lies in the maintenance of combustion at supersonic speeds.

This makes the protection of combustor components very difficult and also complicates ignition, flameholding and fuel-air mixing, especially since the flow must remain essentially shockless throughout the engine. Film cooling may protect the wall and reduce friction but is not conducive to rapid mixing. The supersonic combustion technology maturation program concentrates on combined analytical and some limited experimental studies but the results will not be available until late in FY 1989.

Furthermore none of the effort seems to be directed towards the studies of supersonic combustion instabilities which can be so important to engine performance and are not at all understood. Because of this we recommend that the technology maturation program increase its emphasis on studies of combustion and combustion instabilities at high speeds.

5) <u>SAI Combustion Kinetics Codes</u>

The combustion kinetics codes developed by SAI use a large number of chemical reactions but, to avoid lengthy computer runs, these chemical reactions are cleverly uncoupled from the corresponding conservation equations. This procedure has presumably been used to describe nozzle flows in rockets with a considerable degree of success. Nevertheless it is not clear whether such uncoupling will also be appropriate for the scram jet combustion because

the conditions in the scram jet combustion chamber are quite different from those in the rocket. Careful validation of this procedure is therefore essential before application to engine design.

6) Variation Of Engine Configuration

Single stage to orbit requires continuous thrusting to ever higher velocities. Ram jets and scram jets can efficiently provide such thrusting only by changing their physical configuration. However these changes may trigger undesirable transient behavior, and strong shocks which may result in a loss of thrust. The technology maturation program does not seem to have any elements which either analytically or experimentally address this very important issue at high speeds and we recommend that the program be appropriately reformulated to include it.

7) Off-Design Performance

Ideally, the NASP should be powered by a regeneratively cooled engine with a continuously varying configuration. However, stepwise configuration changes are likely to be much easier to achieve. But such stepwise changes will necessitate compromising engine performance between the changes. To facilitate such an approach off-design engine performance at high speeds will have to be well understood

and therefore we recommend the inclusion of the study of high speed engine performance at off-design conditions into the technology maturation program.

D) Engine-Airframe Integration

The propulsion technology maturation program concentrates on problems peculiar to the so called basic configuration. This configuration is more suitable for a cruising vehicle than a booster. Cruising vehicles resemble airplanes while boosters resemble flying engines. For this reason the engine-airframe integration problems of boosters will be quite different than those of cruise vehicles and the present concentration of the propulsion technology maturation program on the problems of the basic configuration may be somewhat misdirected. Indeed other engine configurations more suitable to NASP's mission as a single stage orbital booster, are presently emerging. We recommend that the propulsion technology maturation program be appropriately modified to also pursue the issues involved in these new configurations.

APPENDIX C

Materials

The present program Technology Maturation Program in materials consists of seven funded tasks in the areas of Advanced Metal Matrix Composites, Rapid Solidification Titanium, Titanium Composites, Exothermic Dispersion Processes, Carbon-Carbon Composites, Ceramic Composites, and Coatings which were discussed, and a series of contractor funded efforts which were not covered.

The program is well planned and well coordinated among the Government and Industry personnel involved. The goals are ambitious but not yet tightly defined, not surprising since the temperature-strength properties which will ultimately be achieved by these materials will determine where they can be used and the degree of active cooling which will be required.

Based upon preliminary design and performance estimates, surface temperatures for the NASP range from in excess of 3000°F to less than 1200°F. Some 15% of the wetted area will be exposed to temperatures above 2600°F where carbon-carbon and ablation materials, or active cooling, will be required, 20% will see temperatures between 1800°F and 2200°F, where ceramic composites show promise, about 50% will reach between 1200°F and 1800°F, where titanium aluminides may be used. Titanium can satisfy the remaining 15% of the structural needs.

Rapid Solidification Titanium compounds were said to be the baseline for a NASP configuration. Data presented showed that Ti_3A_L alloys begin to lose strength at 1000_oF, Ti A_L alloys hold strength to 1500_oF, but are extremely brittle at temperatures below 1000_oF. "Designer" microstructures hold promise of improvement, but control of desired particle sizes and dispersions are challenges. Effects of exposure to hydrogen and dissociated oxygen are severe problems. The XD technology may contribute. The material is promising. Forming, fabricating and fastening needs effort.

Titanium based Metal Matrix Composites also show promise. Reactivity between fibre and matrix requires coating system development. Concerns exist about hydride formation at high temperatures and pressures.

Advanced Metal Matrix Composites appear to have very high payoff but are also extremely high risk because investment only started last year.

There is an existing data base on Carbon-Carbon materials, which show promise of utility up to temperatures above 3000°C. However the gauges required for NASP are much thinner than those used on the Shuttle. The material is very brittle, and exhibits a negative temperature coefficient at lower temperatures (<1000°).

Problems exist with coatings and coating life under oxygen exposure. Fastening will be a challenge. Fabrication cycle is complex, requiring up to six months to make a part.

Fiber reinforced ceramics have the potential of retaining strength up to temperatures between 2500°F and 3000°F. Material options are still being explored. Issues include reactivity with the fibers, fiber coating, fiber degradation at temperature, porosity and cracking during fabrication. Joints, attachments and interfaces are just being addressed.

Coatings will be essential for these materials. They will be exposed to high temperature, high enthalpy, dissociated gasses with high temperature gradients. Coatings tend to be catalytic, which may not be the best approach. Lifetime is also a concern.

Embrittlement from exposure to high temperature, high pressure hydrogen is a problem which will pervade the NASP materials. It is not well understood. The program is now raising contractor awareness of the problem, but has not begun an active program to seek a solution.

The leader of the materials technology team observed that normal materials development takes time - twelve to fifteen years. The NASP accelerated schedule allows only five years.

This disparity was rationalized on the basis that NASP is an experimental vehicle with a relatively short service life, MIL Handbook data properties were not required, and the progam was building off existing technology.

The other side of that coin is that NASP will be a high visibility, manned program in which the technological competence of the United States will be on the line to be judged not just by our own

population, but by the world. If that standard is used, knowledge of material properties at commitment to configuration needs to be almost as good as the MIL-Handbook would require.

The risk in the materials maturation program was summarized as "not a clear go or no-go," rather "how close will we come" and "how soon will we get there."

But "how close will we come" for a vehicle so finely tuned as the NASP is asking how far short of mission objectives will we fall. "How soon will we get there" is an euphuism for "how much will we miss the schedule" and "how much will the cost overrun be."

If the NASP design is based on RSR Titanium alloys and Titanium Metal Matrix materials the ongoing Technology Maturation program is sound, but may not provide necessary data by the presently scheduled date for commitment to configuration decision.

Data required are:

- materials properties
- materials-process compatibility
- damage tolerance
- environmental suitability
- fatigue, fracture and design allowables
- process scaleup

If the other materials discussed above are to be used, the program is grossly underfunded and unrealistic in schedule.

Overall it would appear that the program funding emphasis is out of balance. Too much money may be going into trying to define configuration before the basic data, on which the choice of configuration depends, has been developed.

APPENDIX D

Structures

Summary

A review of mission and specification requirements for the NASP, as related to a structural technology assessment, indicates a structural weight fraction 25-30% less than the current shuttle orbiter and a large increase in mission life.

For some of the missions, performance requirements may dictate higher maximum use temperatures and overall heat loads than seen in the shuttle. Maximum use temperature is probably the limiting factor on desired performance.

The structural designer then has the fundamental task of designing an optimum structures to knowledgeable minimum margins of safety commensurate with man-rating the NASP for flight.

The structural designers' requirements to do this are noted in the following:

1) The material to be used most should be fully characterized from production material (or reasonably close to) - not from small laboratory specimens.

2) The complete operating environment must be determinable and reasonably known.

3) The analysis methodology to determine external loads and therefrom internal loads must be available, verifiable, accurate, and reasonably efficient.

4) Verification of the preceding through adequate ground and subsequent flight tests.

Simply stated, the current ability to meet these structural designers' requirements is marginal-to-not-available. It is considered that Phase 3 cannot realistically be initiated (without excessive risk) until a satisfactory data base is available to the structural designer.

In consideration of all these factors, it is judged that Phase 3 should not be initiated until this required data base is available. The Technology Maturation program should be expanded to include material selection and facilitization as required to produce production size material for characterization and component development.

Material Characterization

The history of development of new materials and construction resulting therefrom indicates a time period of 10-13 years for adequate characterization and maturation of producible designs. While this can probably be accelerated somewhat given funding and manpower, there is no indication that this is happening at this time, nor is it credible to assume that it will be accomplished in the current schedule.

Material characterization is further exacerbated by the extreme thermal/acoustic environment imposed by the mission requirements. Accumulation of this data base is made more difficult because of the facility and instrumentation requirements to test at these temperature and acoustic levels.

A subset of the material characterization deals with methods of fastening - in itself a significant development item dependent upon availability of material.

It is considered that there is insufficient time as currently planned prior to initiation of Phase 3 to accomplish the required task of material characterization and factory facilitization to produce the material necessary for fabrication. It is strongly urged that the time and funding necessary to accomplish these tasks be provided.

Operational Environment and Loads

In most conventional aircraft the structural designer is concerned primarily with aeroelastic loads. Environmental loads (thermal, acoustic, dynamic response) may be critical locally, but are not usually coincident with the critical aero loads and are normally analyzed as separate design conditions.

In addition, the data base and correlation and validation through ground testing is generally well established. Man-rating the flight vehicle for structural integrity is then relatively straightforward.

Such is not the case for the NASP. The loading is aero thermal elastic-acoustic and is coincident at the critical design conditions. The external loading will have to be calculated through the usage of 3D CFD codes which are not yet developed. The uncertainties with respect to flow transition (laminar to turbulent), surface irregularities and potential large deflections caused by thermal gradients (lower to upper surface) combined with the inability to correlate

or validate CFD codes through ground testing make it very difficult to establish the accuracy of the external loading (and therefore, the internal loads and resulting strain levels). In addition, the flight path used to perform the mission has a significant effect on peak temperatures (variations in dynamic pressure and angle of attack). The ability to accurately control the flight path during the mission and the deviations therefrom introduces another variable in the external loading.

The designer is then faced with the dichotomy of attempting to minimize structural weight while considering the range of loading introduced by the uncertainties in the analysis methodology, flight path, surface irregularities, et al. The lack of any significant data base further exacerbates this problem.

The structure cannot be ground tested and man-rating the NASP for structural integrity will be difficult. Since there will be no static or flight test data available, margins of safety based only on allowable strains will not be sufficient. Other safety factors such as limiting material temperatures to values below maximum use temperature (200°F+) must be considered. Development of the analysis methodology coupled with whatever correlation can be obtained from ground testing is a task which must be addressed.

Verification

Validation or correlation of structural and heat transfer codes can be accomplished to some extent up to Mach 10 in ground testing. No correlations of these codes above Mach 10 will be available until

flight testing into this regime. The need for adequate instrumentation with real time data transmission is therefore a flight safety requirement, if envelope expansion is made by a manned flight article.

Static testing of the complete vehicle cannot be accomplished in ground testing. Verification of structural integrity must therefore be generated from a sufficient quantity of component and element testing.

Requirements for certification of structure subjected to combined thermal and mechanical loads are not firm, and current high temperature test techniques and instrumentation are far from satisfactory. Both of these areas need resolution and improvement in order to solidify the component and element test data base.

Conclusion

The impact of structural efficiency on attaining the desired performance is significant and probably ranks equally with the propulsion system. Attainment of a very low structural weight fraction and the ability to operate at the highest maximum use temperatures through an extended life time are critical to success.

The ability of the structural designer to do this requires that the loads (external and internal) be known to a high degree of accuracy which leads to a requirement of a substantial data base on aero-thermal elastic-acoustic loads, comprehensive material characterization, and validated accurate structural and heat transfer codes.

The loading data base and CFD code validation (for Mach 10) will only come from reduction of substantial flight test data in these high Mach regimes. The accuracy of current structural and heat transfer codes is questionable and certainly they are not efficient tools for the structural designer. Required material characterization is not available or scheduled early enough.

To proceed into Phase 3 with this current status of information available to the structural designer is considered an unacceptable risk to program success and in fact could impose serious flight safety risks.

Comprehensive material characterization combined with component testing and improvements in accuracy and efficiency of analysis methodology combined with correlation through ground tests for Mach numbers up to 8-10 probably make the risk manageable by judicious use of design margins (temperature and strain), careful flight test planning and adequate real time data transmission flight instrumentation.

It is recommended that the Technology Maturation program be augmented to obtain adequate material characterization (limited production facilitization is a coincident requirement) and the required improvements in analysis methodology.

Whether the desired and/or required structural efficiency can be obtained with the margin requirement to cover the boundary of uncertainties in the loads is a moot point at present.

APPENDIX E

Control

Overview

The National Aerospace Plane (NASP) Program has some of the most demanding design problems of any flight vehicle development program to date. The extent of coupling between the NASP control system and the vehicle airframe/propulsion system requires that they evolve simultaneously. The degree of uncertainty regarding available component technology and associated performance complicates the task of control system development and mandates early identification of principal design sensitivities and trades. Also, uncertainties regarding environment characteristics demand development of control strategies which maximize available adaptability and authority and minimize the adverse influence of hostile environment effects. All of these considerations are as applicable for development and testing of a research vehicle as for an operational system. Less specific knowledge of the environment during early test flights may actually demand more control system adaptability.

To successfully develop the NASP control system, it is necessary to identify the most significant design concerns involving vehicle control and to initiate a technology development plan capable of addressing the issues. The effort should occur early enough to influence overall vehicle design in a manner that will assure successful vehicle and control system integration. The following material provides a review of the major issues, and summarizes a technology development road including identification of highest priority tasks.

Technology/Design Issues

Resolution of a wide range of issues will be required to successfully control the NASP. The following subsections (the order of which has no particular significance) detail the most serious concerns that are currently recognized. The highly coupled nature of vehicle design and control is apparent in the discussions.

A) Attitude Control Issue

The successful operation of the NASP propulsion system is coupled to the accuracy of attitude state knowledge and control, with the latter subject to effector capability uncertainty.

At high Mach numbers, the air-breathing engine performance will be very sensitive to the vehicle nose shock position relative to engine inlet lip. The shock location is a function of forward body geometry, boundary layer characteristics (tied to Reynolds number effects) and angle of attack. Very small attitude errors would either cause unacceptable shock impingement inside the engine or shocked flow spillage losses which make it difficult for thrust to exceed drag. Accomplishment of the necessary control precision requires good free stream flow data, precise knowledge of the current and projected angle of attack (which partly depends on vehicle thermoelastic geometry changes), and crisp effector response to small attitude change commands.

The control effectors for attitude state management probably will include aerosurfaces, reaction control thrusters, and/or thrust

vector control during powered flight. Aerosurface effectiveness is influenced by boundary layer, wake, aerothermoelastic properties, and physical blockage effects. Thruster torques are affected by plume interaction with the vehicle flow field. Thrust vector control characteristics are tied to propulsion performance which is affected by many of the factors mentioned previously. A versatile technique for blending all available control effectors is necessary to overcome the performance limitations of each type of system, while good sensory data and estimation techniques are required to assess the current authority of a particular effector in order to adapt the control law.

The authority of all rotation control effectors is influenced by vehicle mass property changes (including center of mass shifts) due to propellant depletion. Integrated mission, vehicle, and flight control design must be accomplished to assure that a control strategy exists for successful flight with at least a minimum acceptable attitude control margin.

B) Trajectory Design and Control Issues

Trades between design constraints and propulsion system performance will influence nominal trajectory design and mission feasibility while environment uncertainties will require trajectory adjustments which are limited by coupled vehicle performance and control system robustness. A variety of physical inequality constraints (e.g. dynamic pressure, wing loads, specific force, and thermal loads) strongly influence the acceptable ascent flight trajectory, introducing

critical aero/propulsion design trades, and requiring some parametric trajectory assessment. Higher flight profiles can produce less loading, with associated propulsion performance losses. The higher altitudes also introduce more stochastic variation in the ambient atmospheric conditions which necessitates development of an adaptive control design capable of compensating for the uncertainty. These issues must be assessed in parallel with vehicle design definition.

C) Throttle Dynamics

The air-breathing engine throttle setting is a critical control system parameter. Time response dynamics cannot be arbitrary for stable control. However, the complexity of hypersonic propulsion combustion chemistry introduces some propellant flow demand uncertainty, and active cooling to limit engine strut temperatures and inlet flow boundary layer thickness can introduce a substantial lag in the propellant injector response. An understanding of theses dynamical relationships and associated control system design constraints is required soon.

D) Vehicle Technology and Model Uncertainties

A range of technologies for vehicle subsystem design is under consideration. Considerable uncertainty regarding performance and expected element mass applies to many of the design options. Development of analysis tools which treat design and control with respect to a range of mission objectives in an integrated manner is necessary to assure successful vehicle development. Performance and payload impact and controllability sensitivities

of each major subsystem should be assessed, and a simultaneous determination should be made of those for which detailed knowledge is most critical. In the process the most fruitful technology development activities would be identified.

Partitioning the control system design (including software) into elements sensitive to particular vehicle design characteristics will help isolate and simplify changes necessary to accommodate hardware limitations identified as the vehicle design matures. Early avionics and software architectural characterizations are necessary to achieve this objective. Critical control path test definition, and verification procedure will be simplified too, if given attention in early definition of design elements.

E) Some Real-Time Control Considerations

The following issues will influence the complexity of real-time control requirements and adaptability demands.

- Atmosphere dynamics
- Compensation for most likely anomalies
- Abort scenarios
- Propulsion and aerosurface performance uncertainties
- Manual handling qualities
- Crew control intervention requirements

Flight computer capabilities, the power of real-time trajectory prediction algorithms, and the robustness of control strategies

will collectively determine the extent to which the above list of concerns can be accommodated. However, excepting the atmosphere dynamics and crew intervention requirements, all the issues are vehicle design dependent. Therefore, a satisfactory vehicle design cannot be developed independently of the on-board control system.

Flight Systems Technology Road Map

To accommodate to the issues discussed above, a flight systems technology road map for the NASP has been devised and is structured to be responsive to those items considered critical for program success and the Phase 3 decision point. The main features of the road map, if implemented as planned, appear to have coverage adequate to the task. The first five areas have especially high priority. It must be emphasized however that the highly coupled NASP air frame/propulsion/control system design problem requires the simultaneous development of analytical tools and studies of the integration of the key elements of this complex development. Failure to pursue the full gambit of issue identification and problem solution across the board could leave open a vulnerability fatal to the realization of a successful program. The combination of control related issues and the very broad performance spectrum make the system realization at an early date questionable. On the other hand, the focus provided by the systems concept makes the outlined road map tractable for a technology development.

Highest Priority Road Map Studies

The Flight Systems Team has identified five potential technology

show stoppers in the flight systems area requiring early investigation and development to resolve critical design issues. They include:

1) Integrated control

2) Stability and control in the face of large uncertainties

3) Manual control and flight qualities

4) Evolution of the vehicle in an integrated sense

5) Sensors and instruments

1) Integrated Control

The design of a highly interactive and integrated flight control system utilizing controls to meet a number of usually contradictory requirements will be exaggerated in the case of the aerospace plane. For example, the requirement to stabilize the vehicle attitude along the desired trajectory, to hold the controls, including throttle, in their optimum position for performance, and to adaptively control the vehicle in real time along its trajectory with the required precision is considered to be a major challenge to the present state of the art of integrated control Simultaneous optimization of performance, stability, and flight path control needs to be investigated as one basis of meeting the challenge, and perhaps as a means to identify ways to exploit interaction for performance gains. A task has been structured to ensure that sufficient understanding of this issue is gained to permit the design of the control system for the NASP Vehicle. Fundamental studies of control precision requirements should be made to examine the ability of the flight

control systems to meet those that come from both aerothermal and propulsive system effects. An AFWAL-sponsored study activity should be integrated with the technology maturation activity by forming associate contractor arrangements between contractors. Concepts for on-line trajectory solutions for hypersonic aircraft would be provided to the NASP companies for use in their overall flight trajectory system design. Generation of on-line trajectories for vehicle missions, even during the flight tests of the NASP, is essential to a successful NASP development program.

Successful concepts applied to the SR-71 integrated flight and propulsion control system for Mach 3 cruise will be studied for possible adaptation to the NASP. These have been reviewed extensively within NASA, and have been the basis for successful flight experiments.

2) Stability and Control In The Face Of Large Uncertainties

It is critical to provide sufficient control robustness to assure overall vehicle stability and control in the presence of atmospheric uncertainties, aircraft performance uncertainty, and unmodeled or poorly understood vehicle subsystem models. Shuttle entry experience has shown that significant variations exist in the upper atmosphere which could pose a difficulty for vehicles which operate routinely in that area and require complex control for stabilization or critical trajectory control. There are three elements of this activity that are considered as part of the flight systems technology maturation effort. The first is the creation of an Air Data/Atmospheric Specialists Subgroup

which will collect, develop, and distribute the best data available to describe the upper atmosphere model for the purpose of control system design. The Air Data and Atmospheric Subgroup will have cognizance over the upper atmospheric models issue and air data sensor technology development, and will report to the Flight Systems Team.

The second area identifies vehicle model uncertainty which is always an issue in the flight control system design of any vehicle. As the flight envelope increases, the development of accurate models becomes more crucial in the design and analysis of avionics systems. The vehicle models include the airframe, propulsion system, and all other subsystems which are crucial to describing the operation of the flight control system, but which cannot be studied over the entire flight envelope in ground facilities. These issues should be examined to establish both criteria and approaches for robust flight control in the presence of larger uncertainties than normally considered. This could impact, for example, stability margin criteria.

The third area addresses poorly modeled elements. For the NASP there are modeling issues which have little or no precedent in previous flight control system design. Paramount among these is the issue of closed loop design with aerothermoservoelasticity effects, that is, the aeroservoelasticity effects that are compounded by thermoelasticity with the heated vehicle which, among other things, create challenges in air data interpretation. The Flight Systems Technology Team intends to work cooperatively with the structures task leader in the development of these

models, and then establish unique tasks in the technology maturation effort to accommodate.

3) <u>Manual Control and Flight Qualities</u>

There will be a requirement for piloted control of the NASP. Failure overrides, and abort intervention are always necessary in manned vehicles. Currently there are no handling qualities guides or criteria for many parts of the flight envelope of this vehicle class. In addition, recent work in approach and landing flying qualities of aerospace craft needs to be reviewed for applicability to the NASP design. Handling qualities guides and vehicle response criteria will be generated in conjunction with the NASP contractors in order to assure a common basis for the design of both the vehicle closed loop response and the manual flying qualities of the vehicle. Placement of control surfaces may be influenced by these criteria.

A significant issue is related to the visibility requirements for landing. Landings in early flight tests always start with manual operations, which in the case of the space shuttle have been shown to be difficult. Resolving visibility issues is critical to program success. It is likely that forward vision will not be easily achieved in the design of the vehicle. Technology has advanced in the areas of displays (large format and helmet-mounted) such that it may be possible to utilize them to full benefit to provide a high degree of confidence in the ability to land the vehicle without forward vision. A major study and experimental tests must be conducted to provide this design option to the NASP contractors.

The man-machine interface design for the NASP will be forced to deal with some new and difficult issues. The top level task allocation between the crew, the on-board systems, and the ground systems has not yet been examined in detail. It is probable that focused technology maturation activity will be required in this area as the trade results emerge. The Flight Systems Team should work very closely with the companies to identify technology voids in the design or realization of these systems, and to establish required technology maturation tasks.

4) Evolution Of The Vehicle In An Integrated Sense

The Flight Systems Team will sponsor studies of flight test options for support of the technology maturation areas. Piloting, trajectory, and heating studies must be included. Modeling and simulation are key, with real time capability required to accommodate man-in-the-loop capability. Studies of guidance and navigation requirements to provide autonomy will be needed to deal with the expansive range of eventual high Mach number flight tests, and the blackout from ionized sheaths expected around the vehicle. Flight tests could gradually evolve. For example, one option might be to flight test a propulsion module at subsonic to low supersonic speeds on a testbed aircraft for both technology validation and flight qualification. Other possibilities include the acquisition of aerothermal data from on-going high speed vehicle programs.

Preliminary flight tests plans for the NASP will be developed to the extent required to identify flight test impact on the vehicle itself, and to identify long-term requirements for ground facilities, ground handling, and ground processing to support a timely, productive, and safe envelope expansion of the NASP. An Edwards test team, composed of AFFTC and NASA personnel, is in place. Issues here involve the balance between the flexibility of having man-in-the-loop flight tests and the costs associated with assuring his safety.

5) Sensors and Instruments

The derivation of accurate air data information (Mach number, angle of attack, sideslip) is a potential barrier technology for the NASP vehicle. The degree of control precision of angle of attack and sideslip my require precise estimates (a few tenths of a degree) not possible with current systems. Atmospheric variations and the speed limit for conventional pressure-derived air data probes/sensors make this a very difficult problem. There already is difficuity in achieving the accuracy and reliability of air data measurements at high speed and high altitudes. For example, the shuttle air data system is not employed until the shuttle slows to Mach 3.5. Upper atmosphere disturbances and anomalies may not allow the use of inertial navigation derived parameters solely as a basis of providing the state variables to the flight control system of the NASP. The Air Data and Atmospheric Subgroup (ADAS) should be used to guide the task development in the area.

Tasks need to be pursued which will address the potential development of flush and optical air data systems. In addition an AFWAL SBIR-funded activity should be technically managed from the Flight Systems Team to focus R&D efforts on this problem area.

The thermal environment of the NASP vehicle will create special problems due to direct thermal constraints on subsystem design, and control feedback requirements to limit thermal effects. Hydraulic systems, actuators, avionics, buses, power systems, and other distributed subsystems may be required to be placed in areas where active cooling is not practical or possible. At this time, these areas are considered design grade issues, and focused technology maturation tasks in hardware technology will await the definition of peculiar NASP requirements in the conceptual/preliminary design. If work on high temperature, light weight, low volume, high authority actuators is not initiated early, hinge moments will not be satisfied when they are demanded, as one example.

Additional Recommended Road Map Studies

There are other synergistic and/or long lead time technology studies that have been identified as areas warranting early support. They include:

1) Avionics architecture studies

2) Development of hypersonic-rated hardware

3) Crew vehicle systems

1) Avionics Architecture Studies

The overall architecture of the integrated control system for reliability and fault tolerance for the NASP vehicle is being studied by each NASP company. Considerations include the distribution and level of redundancy of critical sensors, processing systems, buses and bus controllers, actuators and actuator electronics, power, cockpit controls, and software. These issues are being faced in every advanced vehicle design today, and there are many significant engineering design challenges in this area for the NASP, as well. There is also significant government and company R&D activity in this area. If the NASP vehicle preliminary design generates unique requirements for architectural or validation/certification technology, tasks should be developed to address the critical issues.

2) Development of Hypersonic-Rated Hardware

The NASP preliminary design studies have identified several potentially serious hardware deficiencies as it works toward the ultimate realization and implementation of advanced flight systems.

A major issue related to aerospace plane flight systems hardware is in the requirement for extremely light-weight, high power, extreme temperature tolerant flight systems, due to the impact of weight and volume deltas on vehicle design and performance.

Lightweight systems have been highlighted by NASP contractors. The development of specific tasks should be planned to follow

detailed discussions with airframe companies and vendors to determine the level of Internal Research and Development efforts and potential government-sponsored work in this area. Trade sensitivities and technology risk associated with new actuation systems, for example, and weight penalties of less advanced systems should be examined by the companies, and would provide the basis for establishing specific tasks.

Some advanced fuel cell Research and Development (R&D) (solid oxide technology) was sponsored prior to the start of Phase 2. Power generation is still being treated as a trade issue and specific technology maturation tasks should be developed when some convergence is evident.

Applicable antenna data and experience from reentry vehicle development and operations will be gathered for study by the NASP companies. The degree of autonomy and telemetry ties for the NASP is currently a trade issue, and will have a big impact on antenna requirements. When these issues are developed to sufficient degree, specific technology maturation tasks will be considered. A major issue may evolve in the cruise regime where plasma sheaths must be understood before communication with the air vehicle by any means and for any purpose can be guaranteed.

There is some evidence that the design of the NASP vehicle may force ground speeds above those normally utilized in high performance aircraft of today. AFWAL is sponsoring an R&D activity in the area of high speed tires. The Flight Systems Team has decided to track this area very carefully and also

monitor the ground speed issues related to the NASP preliminary design. Should ground speed become a design issue, the AFWAL activity should be accelerated via the technology maturation program. In addition, study activities and results should be relayed to the NASP contractor for vehicle design consideration.

3) Crew Vehicle Systems

Crew escape is of paramount importance in achieving a safe, man-rated design. The trade activities on-going do not indicate new technical areas which should be included in the Technology Maturation Plan. Specific tasks should be considered as more definition of the crew escape issues is developed.

A task should be planned so that the experience gained in crew systems R&D activities related to the space shuttle and the space station will be transferred to the NASP contractors.

Conclusions and Recommendations

The technology road map developed by the flight systems working group has the elements described to provide an adequate understanding and effective development program for NASP. What is not evident is funding and prioritization sufficient to the job done. Controls and flight dynamics optimizations can relieve environments inimical to successful realization of key but very uncertain technologies involved with structures, structural materials, and propulsion systems, for instance. At the levels of program funding currently applied to the flight systems technologies not devoted to the airframe and propulsion systems, it is doubtful that these optimizations can

be examined adequately and that alternatives will be available on a schedule compatible with the airframe/propulsion developments. As a rough example of the amount in contention, it now appears that approximately 1 to 2% of the currently identified funding in the program is intended to cover this functional area. It is patently impossible to reach the goals of the program at the level of funding now allocated to the controls and guidance functions.

APPENDIX F

Computational Fluid Dynamics

The NASP is and of necessity must be the most highly integrated airframe yet to be designed. The thrust must exceed the drag over a wider Mach number range than ever attempted before. The thrust on a jet engine is primarily due to the difference of momentum flux between inlet and exhaust, and the difference of the axial component of the pressure area integral between the inlet and the exhaust nozzle. At low speeds the main contribution to the thrust is the change in momentum. The primary effect of the pressure area integral in the thrust direction is on the "diffuser", which exceeds the pressure area integral over the exit nozzle. As the Mach number increases this balance shifts, the difference in the momentum flux is less, so the axial component of the pressure area integral on the exhaust nozzle is of increasing importance. Thus small changes in pressure, or slopes of surfaces are very important in calculating the thrust from the engine. This implies an accuracy that may well strain the current limits of CFD. Including real gas effects and chemical effects, to say nothing of transition, increases the strain. But the problem is more complex. To accelerate the vehicle, the thrust must exceed the drag. Again, a difference between axial components of pressure-area forces on slender surfaces is required. In addition the skin friction and effects of heat transfer must be included in this difference. Also real gas chemistry and laminar-transition-turbulent-boundary layer transition issues must be dealt with. Thus the ability to accelerate depends on the differences of

two numbers of almost equal size; each of these numbers is itself the difference of two large numbers.

Assuming for the moment that only limited experimental facilities will be available, the first issue will be development of CFD codes. There is evidence that perfect gas Euler codes will work properly for reasonable shaped configurations. However, these codes require about 24 hours to converge at Mach numbers of 20-25. It is not clear how modifications for real gas effects, or how the influence the grid configurations will increase the run time. Automatic adaptive grid procedures are developing rapidly. Thus the increased complexity in the equations may be counterbalanced by a reduced number of grid points. However, including viscosity, chemistry and heat transfer cannot help but increase run times. Inclusion of transition and the effect of turbulent boundary layer is a serious complication, even assuming that one knows how to do it. It is not clear that we do.

Once a code exists, it needs validation at best, or calibration at worst. Validation implies that field data computed by the code have been compared with either experimental data for the same geometry and angles of attack, side slip, Mach numbers and Reynolds numbers, if possible, or with field data from codes that have been previously validated. The range of validation of each of these variables must be determined by individual comparisons. One condition for the comparison is not enough. Once a code is validated the user can feel confident about results within the validation hyperspace. Calibration implies the code is useful after "post processing".

Herein lies the dilemma. Without adequate experimental facilities, validation of data generated by the code is essentially impossible. Even if data from several codes agrees, there is a nagging doubt. Where differences in large quantities are needed to define performance of an aircraft, the doubt is real.

The resolution of the dilemma will be incomplete at best. It will also be untidy, in all probability. Some data will be generated at high Mach numbers using the Langley Research Center helium tunnel. Other data will come from shock tunnels, or other facilities. All this data is likely to be surface conditions. We cannot expect field data in the next few years. The operators of the several available codes will each compute these few cases. Then a judgment will have to be made as to "best" programs.

There is need for clever experiments based upon good physical insight and understanding of what will stress a code. If one is clever enough these experiments should illustrate effects one at a time, and then 2x2 and more. Chemistry and combustion will be one dominant problem. Another is the start and length of transition. A third, is the nature of turbulence at M=15 or 25. Finally there is the effect of shock on shock, shock-boundary layer and shock-radiation interaction. Note the latter includes three unknowns, skin friction heat transfer rate and gray body emissivity. Clearly design of aerodynamic experiments and the apparatus will be challenging.

One perfect gas Euler calculation can require about 24 hours of computer time at M=25 to converge. The ATF design required about 6500 points to fill the data base. A point is a geometry, angle of attack, angle of sideslip, Mach number, altitude, cg location throttle setting and presumably Reynolds number. Rate effects must ultimately be included to determine handling qualities. For the number of independent variables, this is a reasonably sparse data base. Estimates should be developed for the NASP computational requirements.

APPENDIX G

Contractor Response

The Task Force met with the eight Phase 2, Part II contractors during the period June 23 to June 25, 1987. Each meeting included a half hour closed session with only contractor personnel and Task Force members present.

The Appendix, containing summaries of points made in each of those discussions, is withheld from this copy of the report, because of the potential for competition sensitivity.